

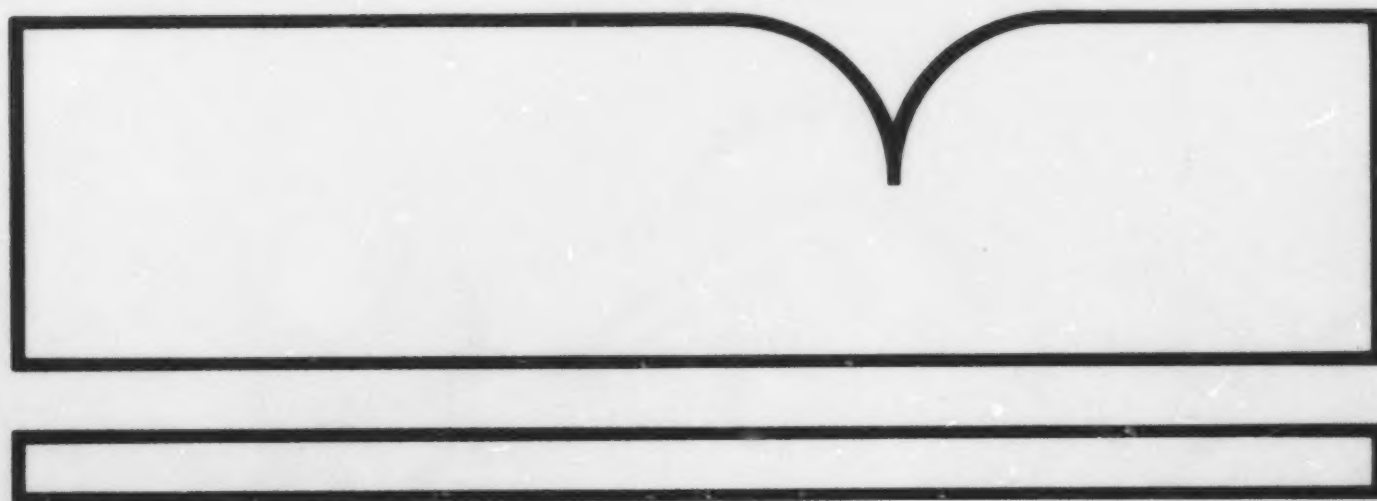
Simplified Analysis of
Two-Well Tracer Tests in
Stratified Aquifers

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A Simplified Analysis of Two-Well Tracer Tests in Stratified Aquifers

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ABSTRACT

This paper illustrates several interesting effects of aquifer stratification on the results of two-well tracer tests by means of a simplified computer model. In the model, it is assumed that the aquifer is horizontal, confined, of constant thickness and porosity, and perfectly stratified in the vicinity of the test wells. The nonuniform advection pattern is taken into account in detail by the model, but the local hydrodynamic dispersion is completely neglected. This simplified model has been verified in part by comparisons with available analytical solutions valid for homogeneous aquifers and in part by comparisons with the results of a two-well field experiment of Pickens and Grisak (1981a) which was performed in a locally stratified aquifer. The applications of the model to several field situations with assumed values of the relevant parameters show that the concentration versus time breakthrough curve measured at the withdrawal well during a standard two-well test would be very sensitive to variations of the hydraulic conductivity in the vertical. Without the use of supplementary observation wells with isolated multilevel sampling points, the standard test would give little useful information about the hydraulic and dispersive characteristics of an aquifer. Factors such as the length of the tracer injection period, the use of recirculation and the physical size of the experiment all have a strong effect on the breakthrough curve measured at the withdrawal well, making the interpretation of field results difficult unless aquifer stratification is measured and properly taken into account.

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INTRODUCTION

Analysis and prediction of contaminant migration in aquifers generally involve the use of some form of the advection-dispersion equation (Fried, 1975; Anderson, 1979, 1984). Parameters which enter the various forms of this equation include those related to adsorption-desorption, chemical and biological reactions, advective transport, and hydrodynamic dispersion (Pickens and Grisak, 1981b). All such parameters would have to be measured or estimated in order to apply an advection-dispersion model to an actual contamination problem.

In this paper, we are concerned with the standard two-well tracer dispersion field tests which are sometimes used to measure effective full-aquifer dispersion coefficients or dispersivities (Grove and Beetem, 1971; Hoopes and Harleman, 1967; Pickens and Grisak, 1981a). In a standard two-well test, a conservative tracer of known concentration is added to water which is pumped into an aquifer through a fully-penetrating well (injection well) and simultaneously pumped out of a nearby fully-penetrating well (withdrawal well). While this pumping is taking place, the concentration of tracer in the withdrawn water is measured and recorded as a function of time. The concentration versus time data from the pumping well are then analyzed to estimate various parameters such as the effective porosity and the effective full-aquifer dispersivity (see, e.g., Grove and Beetem, 1971; Pickens and Grisak, 1981a). In more detailed two-well tests, one or more multilevel sampling observation wells may be used in addition to the pumping wells. These are used to obtain concentration data from discrete locations at different depths in the formation during the tests, and these

data may be used to obtain estimates of the vertical distribution of horizontal hydraulic conductivity in the aquifer in the vicinity of the test wells (Pickens and Grisak, 1981a).

In most previous analyses of two-well tests, the aquifer has been assumed to be homogeneous, and two-dimensional areal advection-dispersion models have been used to interpret the experimental data. Until recently (see Pickens and Grisak, 1981a; Molz *et al.*, 1983a; Falta, 1984; GeoTrans, 1984), possible stratification of the aquifer (the existence of layers having different hydraulic conductivity) has been ignored in these analyses. Recent studies have indicated, however, that stratification may have significant effects on the results of such field tests, and on the transport and dispersion of contaminants in aquifers in general (Pickens and Grisak, 1981a; Molz *et al.*, 1983a; Güven *et al.*, 1984; Gillham *et al.*, 1984).

The objective of this paper is to present some simple analyses carried out to study the possible effects of aquifer stratification on the results of standard two-well tests. A simple computer model, called the "two-well advection model" (TWAM), has been developed for this purpose. In the model, it is assumed that the aquifer is horizontal, confined, of constant thickness and porosity, and perfectly stratified in the vicinity of the test wells. Perfect stratification means that the horizontal hydraulic conductivity is a function of the vertical coordinate only, and other local medium properties are either constant or depend on the vertical coordinate only. With these assumptions, the local seepage velocity is not uniform over the thickness of the aquifer, but varies with the vertical coordinate. Consequently, advection rates of the tracer also depend on the vertical coordinate. The two-well model TWAM takes into account the depth-dependent advection in the horizontal planes, but neglects completely the local hydrodynamic dispersion (i.e., diffusion and mechanical dispersion at the representative elementary volume scale). The model has been verified in part by comparisons with available analytical solutions valid for homogeneous aquifers and in part by comparisons with the results of a two-well field experiment of Pickens and Grisak (1981a) which was performed in a locally stratified aquifer. After verification of the model, several cases with assumed values of the relevant parameters have been studied using TWAM to illustrate the effects of various factors on the results of the two-well tests.

The present simple analyses illustrate several interesting effects of aquifer stratification on the

results of standard two-well tests. Since local hydrodynamic dispersion has been completely ignored in the present analyses, the results are necessarily approximate. However, the effects of local dispersion in such tests will usually be secondary and often negligible compared to the effects of stratification. This is supported by the results of more involved analyses which have been performed recently utilizing the data of Pickens and Grisak (1981a) and a three-dimensional computer model including the effects of local hydrodynamic dispersion in the longitudinal, lateral, and vertical directions (GeoTrans, 1984).

TWO-WELL TEST

A standard two-well tracer dispersion experiment involves the simultaneous operation of an injection well and a withdrawal well, both of which are fully screened and fully penetrating over the entire thickness of the aquifer (Figure 1). Water is injected into the injection well at a steady flow rate, Q , and is removed from the withdrawal well, usually at the same rate, although two-well tests have been performed in which the flow rates

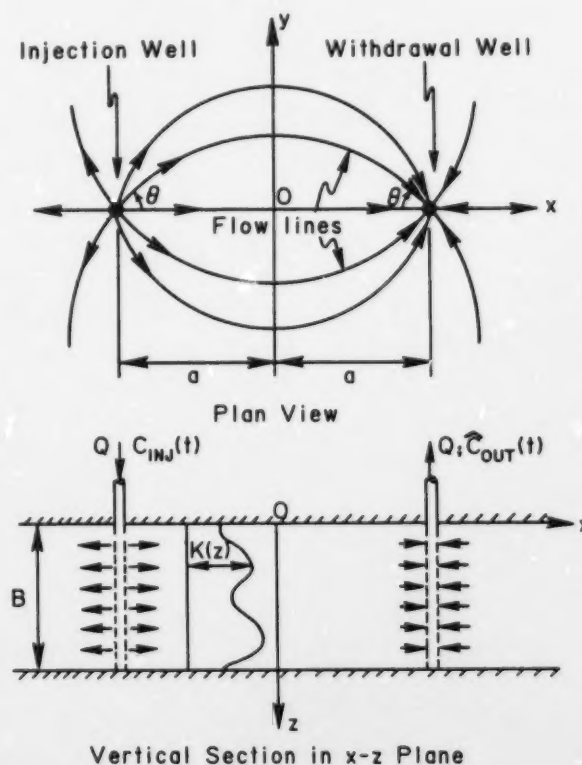


Fig. 1. Two-well test in a stratified aquifer.

in the two pumping wells were not equal (see, e.g., Gelhar, 1982). A conservative tracer of known concentration, $C_{in}(t)$, is added at the injection well for a period of time, t_{in} , and the concentration of tracer in the water leaving the withdrawal well, $\hat{C}_{out}(t)$, is measured and recorded as a function of time to give a concentration versus time breakthrough curve. The tracer injection period is usually short compared to the total time of the experiment. A two-well test may be carried out in either a recirculating or nonrecirculating mode. In the recirculating mode, the water pumped from the withdrawal well is piped back to the injection well, where it is injected back into the aquifer. The concentration of tracer entering the injection well during a two-well test with recirculation, $C_{inj}(t)$, will be equal to $C_{inj}(t) = C_{in}(t) + \hat{C}_{out}(t)$, approximately, assuming that the travel time in the pipe joining the two wells is negligible. In the nonrecirculating mode, the water produced from the withdrawal well is not used. A separate water supply, usually a well in the same aquifer but not near the two test wells, provides the injection water. The injection tracer concentration in this case is $C_{inj}(t) = C_{in}(t)$. The concentration versus time data obtained in this manner at the withdrawal well is then used, together with the assumption of a homogeneous aquifer of constant thickness, to obtain estimates of the parameters such as the effective porosity and the effective longitudinal dispersivity (Grove and Beetem, 1971; Grove, 1971). In some two-well tests, observation wells containing isolated multilevel samplers are installed between the injection well and the withdrawal well in order to sample the tracer concentration in the aquifer at different elevations during the experiment. From the tracer arrival times at different isolated sampling points in a multilevel sampling observation well, the variation of horizontal hydraulic conductivity in the vertical may be inferred (see, e.g., Pickens and Grisak, 1981a) if it is assumed that the aquifer is perfectly stratified, and of constant thickness and porosity in the vicinity of the test wells.

By considering a homogeneous aquifer having constant thickness, Hoopes and Harleman (1967) have theoretically studied several aspects of a nonrecirculating two-well test. In such an aquifer, the flow pattern is that of a two-dimensional (x-y) source-sink combination as shown in Figure 1 [see also Hoopes and Harleman (1967, Figure 1), and Grove and Beetem (1971, Figure 10)]. With these assumptions, Hoopes and Harleman (1967) obtained analytical solutions for the tracer

concentration in the aquifer and at the withdrawal well during a two-well test for four different cases: (1) advection with no local dispersion, (2) advection with local dispersion along the streamlines, (3) advection with local dispersion transverse to the streamlines, and (4) advection with local dispersion along and transverse to the streamlines. From their work, Hoopes and Harleman (1967) concluded that the full-aquifer dispersion seen in the concentration versus time breakthrough curve measured at the withdrawal well in most two-well tests in homogeneous aquifers is mainly due to the advection pattern. The tracer added at the injection well travels along different streamlines between the injection well and the withdrawal well (see Figure 1), with the tracer moving along each streamline requiring a different travel time to reach the withdrawal well.

Mercado (1967) and others have suggested that if an aquifer is stratified, the concentration versus time breakthrough curve measured at the withdrawal well during a two-well test will be further affected by the nonuniform distribution of horizontal hydraulic conductivity in the vertical. However, the possible effects of stratification on a two-well test have not been studied in detail in the past.

NUMERICAL MODEL

In order to study the effects of stratification on the results of two-well tests, a simple computer program called the "two-well advection model" (TWAM), was developed. This program calculates the concentration of tracer leaving the withdrawal well during a two-well test by simulating the advective flow pattern in a perfectly stratified aquifer of constant thickness and uniform porosity. In a steady-state two-well test conducted in such an aquifer, it can be shown that the flow lines are horizontal (in the x-y plane as defined in Figure 1), and that the flow pattern in every horizontal (x-y) plane is the same as the flow pattern produced by a two-well experiment in a homogeneous aquifer. In a stratified aquifer, the horizontal hydraulic conductivity, K , is a function of the vertical coordinate, z , i.e. $K = K(z)$. If the average flow rate per unit aquifer thickness, $\bar{q}$, is defined as the total flow rate, Q , divided by the aquifer thickness, B , the flow rate per unit thickness at any elevation in a stratified aquifer, $q(z)$, may be found by

$$q(z) = [K(z)/\bar{K}] \bar{q} \quad (1)$$

where $\bar{K}$ is the depth-averaged hydraulic conductivity defined as

$$\bar{K} = 1/B \int_0^B K(z) dz \quad (2)$$

Hereafter, the ratio $[K(z)/\bar{K}]$ will be denoted by $\psi(z)$. In the computer program TWAM, the time over which a two-well experiment is conducted is divided into equal time steps, Δt . During each time step, the tracer concentration entering the injection well, $C_{inj}(t)$, and the tracer concentration leaving the withdrawal well, $\hat{C}_{out}(t)$, are calculated. This is done as follows. The stratified aquifer is approximated by NL discrete layers, each having a thickness b_j and hydraulic conductivity K_j where j is an integer corresponding to a horizontal layer in the aquifer, and a method similar to that developed by Grove (1971), and Grove and Beetem (1971) for use in a homogeneous aquifer, is used to determine the tracer concentration, $C_{out}^{j,k}$, (k is an integer corresponding to the time step) entering the withdrawal well from each layer. While the present approach is similar to that of Grove and Beetem (1971), the effects of local dispersion are neglected completely in the present model [the Grove (1971) model can include longitudinal dispersion along the flow lines], and only the effects of advection are considered. The flow regime between the injection well and the withdrawal well is approximated by many thin crescents which match the pattern of the flow lines between the two wells. Because of the symmetry of the flow pattern about a vertical (x - z) plane passing through the two wells, only half of the flow field is considered in the actual calculations.

As in the Grove (1971) model, 180 crescents are used in the present calculations with the flow rate in each crescent the same for a given layer. In a homogeneous aquifer, the water travel time along a streamline from the injection well to the withdrawal well, t_θ , is given by (Grove, 1971; Grove and Beetem, 1971; Hoopes and Harleman, 1967)

$$t_\theta = \frac{4\pi na^2}{\bar{q} \sin^2 \theta} (1 - \theta \cot \theta), \quad 0 < \theta \leq \pi \quad (3)$$

$$\text{and} \quad t_\theta = \frac{4\pi na^2}{3\bar{q}}, \quad \theta = 0 \quad (4)$$

In (3) and (4), n is the porosity, a is one-half the distance between the wells, and θ is the angle (in radians) formed between the particular flow line and the x -axis where the flow line meets a well (see Figure 1). To use equations (3) and (4) in a layer of a stratified aquifer, the average flow rate per unit aquifer thickness, $\bar{q}$, is replaced by the flow rate per unit aquifer thickness for the layer

of interest, q_j , which is given by (1). Thus, an average travel time, $\bar{t}_\theta^j$, for each crescent in each layer can be calculated. The average travel time, $\bar{t}_\theta^j$, for a particular crescent is defined as the arithmetic average of the travel times along the two adjacent streamlines defining the particular crescent. During each time step in each layer in each crescent, the elapsed time t (equal to the time step size, Δt , multiplied by the number of time steps which have passed, k) is compared with the average travel time, $\bar{t}_\theta^j$, and the travel time plus the tracer injection time, $\bar{t}_\theta^j + t_{in}$. If the elapsed time is less than the average travel time in a particular crescent at a given level, the concentration in that crescent at that level at the withdrawal well is zero. If the elapsed time is greater than the travel time, but less than the travel time plus the tracer injection time, the concentration in a particular crescent at a particular level at the withdrawal well is equal to C_{inj}^{k-m} , where $C_{inj}^{k-m} = C_{inj}(t - \bar{t}_\theta^j)$, t is the elapsed time ($t = k\Delta t$), and m is the number of time steps it takes for the tracer to travel between two wells ($m = \bar{t}_\theta^j/\Delta t$) in the particular crescent at the particular level. If the test is of the nonrecirculating type, $C_{inj}^{k-m} = C_{inj}(t - \bar{t}_\theta^j) = C_{in}(t - \bar{t}_\theta^j) = C_{in}^{k-m}$; if it is of the recirculating type, $C_{inj}^{k-m} = C_{in}^{k-m} + \hat{C}_{out}^{k-m}$. If the test is of the nonrecirculating type, and the elapsed time is greater than the travel time plus tracer injection time, then the concentration at the withdrawal well in the crescent in the layer is again zero. If the test is one with recirculation, then the concentration at this time entering the withdrawal well from the crescent will be $C_{inj}^{k-m} = \hat{C}_{out}^{k-m}$ (recall that $C_{inj}^k = C_{in}^k + \hat{C}_{out}^k$). In each layer, the concentrations from the crescents are summed and divided by 180. This gives the average concentration, $C_{out}^{j,k}$, of tracer in the layer j at time k at the withdrawal well. Then a flow-weighted average given by

$$\hat{C}_{out}^k = 1/B \sum_{j=1}^{NL} b_j \psi_j C_{out}^{j,k} \quad (5)$$

is used to calculate the tracer concentration leaving the withdrawal well. These calculations are repeated in each time-step to produce the concentration versus time breakthrough curve for the tracer-labeled water leaving the withdrawal well. A complete listing of TWAM is presented in the Appendix.

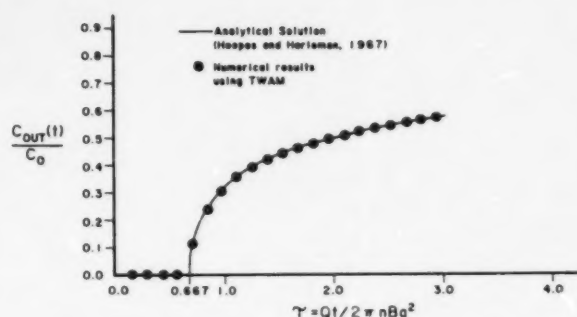


Fig. 2. Comparison of TWAM results with an analytical solution.

COMPARISON WITH AN ANALYTICAL SOLUTION

In Figure 2, an analytical solution obtained by Hoopes and Harleman [1967, Figure 2, equation (16)] for the tracer concentration at the withdrawal well during a two-well test is plotted along with the results of the computer model, TWAM. This analytical solution applies to a test in a homogeneous aquifer with continuous tracer injection at a constant concentration with no recirculation. The effects of local dispersion are not considered. In Figure 2, C_{out} is the concentration at the withdrawal well, C_0 is the constant concentration of tracer injected into the injection well, and the nondimensional time, τ , is defined as

$$\tau = \frac{Qt}{2\pi nBa^2} \quad (6)$$

where t is the elapsed time since the beginning of the experiment. The numerical calculations were made using 21 time steps and 180 crescents with a nondimensional time-step size of 0.14007. Only one layer was used because of the homogeneous aquifer assumption. The numerical calculations using TWAM required about one second of computer time on an IBM 3033 computer, and show close agreement with the analytical solution.

SIMULATION OF A FIELD EXPERIMENT

A very detailed two-well recirculating tracer experiment was performed by Pickens and Grisak (1981a) in an 8.2 meter thick locally stratified, granular, confined aquifer. The porosity varied between 0.33 and 0.43, with an average of about 0.38. The two wells were separated by a distance of 8 meters with five observation wells, each containing isolated multilevel sampling devices, installed between the two pumping wells. Tracer was injected for 3.22 days of the 15 day experi-

ment, with an average injection-withdrawal flow rate of 1.62 m³/hr. From the tracer arrival times at the many sampling points in the observation wells, Pickens and Grisak (1981a) obtained the vertical distribution of horizontal hydraulic conductivity, K , at several locations between the two pumping wells. In their Table 10, the hydraulic conductivity profiles from observation wells located 4 and 7 meters from the injection well are presented in detailed numerical form. These profiles are expressed in terms of a relative conductivity, K_{rel} , which is defined as K/K_{max} , where K_{max} is the maximum hydraulic conductivity inferred from the measurements at the particular observation well used to obtain the conductivity profile. In their Table 7, Pickens and Grisak (1981a) give the average relative hydraulic conductivity, $\bar{K}_{rel}$, from the observation wells located 4 and 7 meters from the well. Because $K_{rel}/\bar{K}_{rel} = K/\bar{K} = \psi$, the data are easily arranged into the nondimensional form used by TWAM. The hydraulic conductivity profile from 7 meters from the injection well, along with the other relevant information from the two-well test of Pickens and Grisak (1981a), were used in a TWAM simulation.

The results of this simulation are presented in Figure 3 along with the three-dimensional model results of GeoTrans (1984) obtained with some arbitrary values for the local dispersivities and the results of Pickens and Grisak (1981a) obtained using the Grove (1971) two-well dispersion model assuming a homogeneous aquifer with a longitudinal dispersivity, α_L , of 50 centimeters. In Figure 3, C_0 is the average concentration of tracer injected into the injection well assumed to be constant over the injection period, and $\hat{C}_{out}$ is the concentration leaving the withdrawal well. Superficially, the

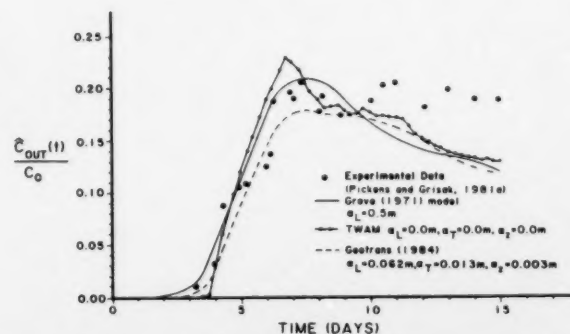


Fig. 3. Comparison of TWAM results with Grove (1971) model, GeoTrans (1984) model, and field experimental results.

results of the Grove (1971) model and TWAM seem to display some similarity. Both seem to match approximately the early part of the curve well but underestimate the later part of the curve. However, there is a fundamental difference in these two calculations. The Grove model assumes homogeneous aquifer characteristics, and is a curve-fitting procedure used to determine an apparent full-aquifer dispersivity. This "dispersivity" is not an aquifer property; if the separation between the injection and production wells were changed, the full aquifer dispersivity would change also (Molz *et al.*, 1983a; Güven *et al.*, 1984). TWAM, on the other hand, by using known information about the aquifer, attempts to predict the breakthrough curve with no fitting of the data. The same is true for the three-dimensional model which uses the same information as TWAM but, in addition, considers the possible effects of local hydrodynamic dispersion. Evidently, such dispersion was very small in the Pickens and Grisak (1981a) experiments, certainly less than the dispersion that would result from the arbitrary dispersivity values used in the three-dimensional model. Indeed, Pickens and Grisak (1981a) estimated an average local longitudinal dispersivity of about 0.007 m for their aquifer from their field measurements, while the arbitrary local longitudinal dispersivity value used in the three-dimensional calculations was 0.062 m.

The reasons for the discrepancy between the experimental data and numerical model results during the later part of the experiment are not entirely clear. Although Pickens and Grisak (1981a) attributed the difference in the Grove (1971) model results and the field data to the fact that the Grove (1971) model considered only one recirculation of tracer, TWAM, using continuous tracer recirculation, was not able to match the later part of the curve significantly better. The differences may be due to several factors such as variations of the horizontal hydraulic conductivity in the horizontal (x-y) plane, or the presence of very high or very low conductivity layers or lenses which were not detected by the multilevel samplers. These factors are not taken into account by any of the mathematical models.

A STUDY OF VARIOUS FACTORS AFFECTING TWO-WELL TESTS

In order to test the sensitivity of two-well tests to various parameters, several simulations were carried out using TWAM. Throughout these simulations, the flow rate and aquifer characteristics were held constant while the distance between the

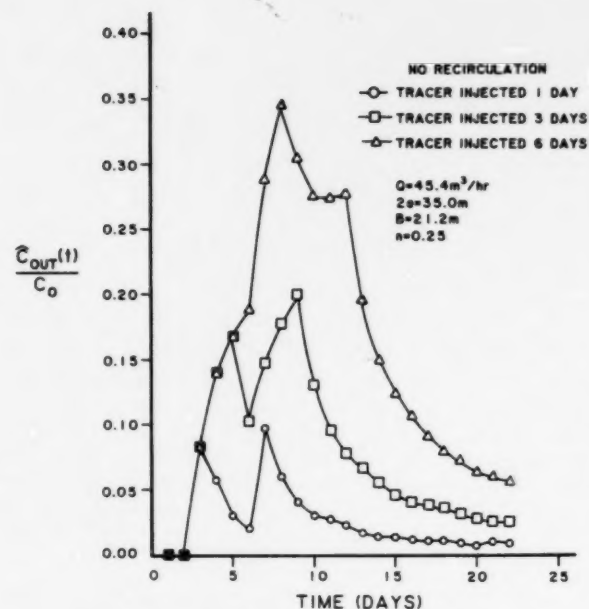


Fig. 4. TWAM simulations of two-well tests without recirculation. Distance between the wells is 35.0 m.

wells and the length of the tracer injection period were varied. Several calculations were made with and without recirculation of tracer. The time-step size used in the calculations was one day, and each computer run required about two seconds of computer time on an IBM 3033. The aquifer thickness, hydraulic conductivity profile, and porosity used in the simulations are partly hypothetical and partly based on the results of previous aquifer thermal energy storage experiments conducted near Mobile, Alabama in a confined aquifer (see Molz *et al.*, 1983b). The aquifer is assumed to be 21.2 meters thick with an estimated average porosity of 0.25. For the simulation, the aquifer was assumed to consist of three layers. The upper and lower layers were assigned a hydraulic conductivity equal to 0.4 times the conductivity of the center layer. The upper layer was 10 meters thick, the center layer was 5 meters thick, and the lower layer was 6.2 meters thick.

In Figure 4, the results of the simulations are shown for a case where the two wells are separated by a distance of 35 meters and where there is no recirculation of tracer. Figure 4 shows the breakthrough curves, $\hat{C}_{out}/C_0$ versus time, t , at the withdrawal well, where C_0 is the concentration of tracer entering the injection well. From these breakthrough curves, the effect of different tracer injection periods can be clearly seen. In the simulation where tracer was injected for six days, the

breakthrough curve has a very steep peak followed by a small plateau, and then a gradual smooth tail. However, in the simulations where tracer was injected for one day and three days, the breakthrough curves show two definite peaks instead of only one as was seen in the six-day tracer injection. The reason for this is that in the aquifer, the tracer slug travels at different speeds in the different layers. When the tracer injection period is short, or when the distance between the two wells is large, a separation of the initially continuous tracer slug may occur resulting in breakthrough curves having more than one peak. When tracer is injected for a longer period, or when the wells are close together, the tracer in the different layers may not become separated. Of course, if the effects of local dispersion were included, or if the hydraulic conductivity variations were not as large as the ones used in these simulations, the separation of the tracer slug in different layers would not be as pronounced.

In Figure 5, six tests were considered in which the two wells were separated by a distance of 38.1 meters, and in addition to the different tracer injection periods used, the simulations were carried out with and without recirculation. Again, the breakthrough curves produced when tracer was injected for one and three days have two very distinct peaks, while the breakthrough curves for the six-day injection did not. The effects of recirculation begin to be felt after about eight days (twice the time it took for the tracer to first appear in the withdrawal well). As one would expect, recirculation has a relatively greater effect on the breakthrough curve when tracer is injected for longer periods.

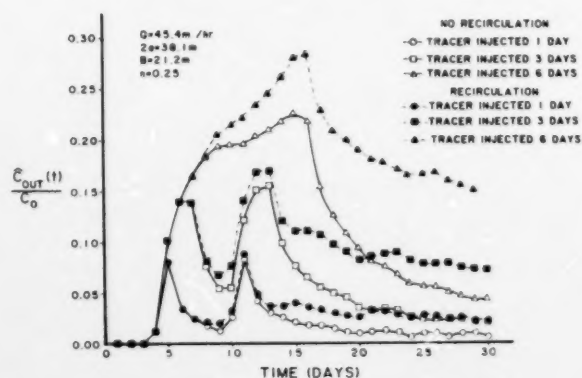


Fig. 5. TWAM simulations of two-well tests with and without recirculation. Distance between the wells is 38.1 m.

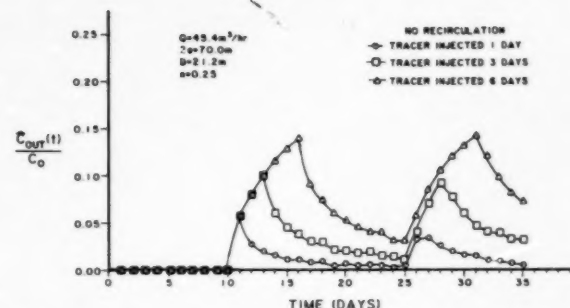


Fig. 6. TWAM simulations of two-well tests without recirculation.

In Figure 6, breakthrough curves are shown for experiments in which the two wells were separated by 70.0 meters. In these simulations, the distance between the wells has become large enough so that even the six-day tracer injection breakthrough curve has two peaks. By injecting tracer for a longer period, say 20 days, it would be possible to produce breakthrough curves having one peak.

CONCLUSIONS

The present simplified analyses show that the concentration versus time breakthrough curve measured at the withdrawal well during a standard two-well test would be very sensitive to variations of the hydraulic conductivity in the vertical. Without the use of multilevel observation wells, the test would give little useful information about the hydraulic and dispersive characteristics of the aquifer, such as aquifer stratification or values of local dispersivities, although a multi-peaked breakthrough curve, when it occurs, would indicate that layers of different hydraulic conductivity exist in the vicinity of the test wells. Factors such as the length of the injection period, the use of recirculation, and the physical size of the experiment all have a strong effect on the breakthrough curve measured at the withdrawal well making the interpretation of field results difficult, unless aquifer stratification is measured and properly taken into account.

It may be useful to note that these conclusions about the two-well test are also supported by the results of more involved calculations carried out by means of a three-dimensional computer model (GeoTrans, 1984) which include the effects of local dispersion in all three principal directions in addition to the effects of stratification. Additional information about these more detailed calculations will be presented separately.

Appendix. Complete Listing of TWAM

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*****
C TWO-WELL ADVECTION MODEL
*****
C
C INPUT DATA
C
C
C q= pumping rate (l**3/t)
C b= aquifer thickness (l)
C a= one-half distance between pumping wells (l)
C delt= length of tracer injection period (t)
C por= porosity (unitless)
C dt= time-step size (t)
C t= total time of experiment (t)
C nl= number of layers in aquifer (unitless)
C icon= 1 for unsteady input concentration, otherwise
C       a steady input concentration will be used
C irec= 1 for no recirculation, otherwise recirculation
C       will be used
C bl(i)= thickness of layer i (l)
C psi(i)= hydraulic conductivity of layer i divided
C         by the average hydraulic conductivity (unitless)
C cin(nnn)= input concentration during each time-step
C           of delt if icon=1, not used otherwise
C
C DEFINITION OF VARIABLES
C
C
C bob(i)= thickness of layer i divided by the aquifer
C         thickness, b
C nb= total number of time-steps used in simulation
C time= elapsed time during simulation
C relcon= concentration of tracer in each layer
C         during each time-step at the withdrawal
C         well
C c= conversion factor from degrees to radians
C ql= flowrate per unit aquifer thickness in each layer
C bb= part of the tracer travel time calculation for
C     each streamline in each layer
C t(i)= tracer travel time for each streamline, i, in
C     each layer
C s= angle between streamline and a line between the
C     two wells, measured at one of the wells
C tave= average travel time for the crescent formed
C       between streamlines i and i-1
C kn= length of tave in terms of time-steps
C plug= time required for initial slug of tracer to
C       pass through crescent
C knn= length of plug in terms of time-steps
C kk= elapsed time - travel time in terms of time-steps
C con= concentration of tracer entering the withdrawal
C     well from a particular crescent in a layer during
C     a time-step
C rcon= con divided by the number of crescents in each
C     layer
C relay(nlay,nnn)= concentration of tracer in each layer
C                  during each time-step at the withdrawal well
C avecon(knlay)= flow-weighted concentration entering the
C                 withdrawal well from each layer
C xcon(nnn)= concentration of tracer leaving the withdrawal
C            well during each time-step
C tau= dimensionless time
C
C
C *****
C
C program twam
C dimension t(200),avecon(500),relay(50,500),bob(50),
C #bl(50),psi(50),xcon(500),cin(500)
C 3 format (t5,q='f10.4,5x,b='f10.4,5x,a='f10.4,
C #5x,delt='f10.4,/,t5,t='f10.4,5x,dt='f10.4,
C #5x,por='f7.4,/,t5,nl='f5.5x,icon='f5.5x,
C #irec='f5,/,/)
C 101 format (f10.6)
C 102 format (t5,time='f10.4,5x,input concentration
C #='f10.6)
C 5 format (7f10.5,/,3i5)
C 8 format (2f8.5)
C 7 format (t5,i5,5x,f10.4,4x,f8.5,/)
C 513 format (t6,'layer',11x,'bl',8x,'psi',/)
C 508 format (t5,f10.4,10x,f9.6,10x,f9.6,/)
C 509 format (/,/,t11,time',5x,dimensionless time',
C #3x,'withdrawal concentration',/)
C *****read input data*****
C read (5,5) q,b,a,delt,t,dt,por,nl,icon,irec
C write (6,3) q,b,a,delt,t,dt,por,nl,icon,irec
C write (6,513)
C do 511 i=1,nl
C
C read (5,8) bl(i),psi(i)
C write (6,7) i,bl(i),psi(i)
C bob(i)=bl(i)/b
C *****
C 511 continue
C if (icon.ne.1) go to 200
C write (6,210)
C 210 format (t10,'unsteady input concentration',/)
C go to 220
C 200 write (6,230)
C 230 format (t10,'steady input concentration',/)
C 220 if (irec.ne.1) go to 240
C write (6,250)
C 250 format (t10,'no recirculation',/)
C go to 260
C 240 write (6,270)
C 270 format (t10,'recirculation',/)
C 260 nb=t/dt
C write (6,509)
C *****start time loop*****
C do 800 nnn=1,nb
C time=nnn*dt
C if (time.gt.delt) go to 100
C if (icon.ne.1) go to 99
C *****read in unsteady input concentration if icon=1*****
C read (5,101) cin(nnn)
C write (6,102) time, cin(nnn)
C go to 100
C *****steady input concentration if icon not equal to 1*****
C 99 cin(nnn)=1.
C ***** start layer loop*****
C 100 do 810 nlay=1,nl
C relcon=0
C pi=3.14159265
C c=pi/180
C *****calculate flowrate per unit aquifer thickness in each layer***
C ql=q*psi(nlay)/b
C *****calculate tracer travel time along a line connecting the wells*
C bb=por*pi*a*a*.4/.q
C t(i)=bb/3
C *****start crescent loop*****
C do 720 i=2,180
C ii=i-1
C s=s*pi
C *****calculate tracer travel time along each streamline****
C t(i)=bb*(1-s*(1./tan(s)))/(sin(s)*sin(s))
C *****calculate average travel time between streamlines*****
C tave=(t(i)-t(ii))/2.
C kn=tave/dt
C *****calculate time for initial slug to pass through crescent****
C plug=tave-delt
C knn=plug/dt
C *****elapsed time - travel time*****
C kk=nnn-kn
C *****determine concentration of tracer entering withdrawal***
C *****well based on elapsed time, travel time, length of*****
C *****tracer injection period, and recirculation*****
C if (nnn.gt.kn) go to 750
C con=0
C go to 770
C 750 if (nnn.gt.knn) go to 760
C if (irec.eq.1) go to 150
C con=cin(kk)+xcon(kk)
C go to 770
C 150 con=cin(kk)
C go to 770
C 760 if (irec.eq.1) go to 765
C con=xcon(kk)
C go to 770
C 765 con=0.
C 770 rcon=con/180.
C *****sum contribution from each crescent*****
C relcon=relcon+rcon
C *****end of crescent loop*****
C 720 continue
C relay(nlay,nnn)=relcon
C *****end of layer loop*****
C 810 continue
C xcon(nnn)=0
C *****calculate flow-weighted concentration at withdrawal well****
C do 507 knlay=1,nl
C avecon(knlay)=relay(knlay,nnn)*bob(knlay)*psi(knlay)
C xcon(nnn)=xcon(nnn)+avecon(knlay)
C 507 continue
C *****dimensionless time*****
C tau=(q*(time))/(2.*pi*por*b*a**2)
C write (6,508) time,tau,xcon(nnn)
C *****end of time loop*****
C 800 continue
C stop
C end

```

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